Kinematics of Circumgalactic Gas

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Background Beacons

3D Galaxy Orientations

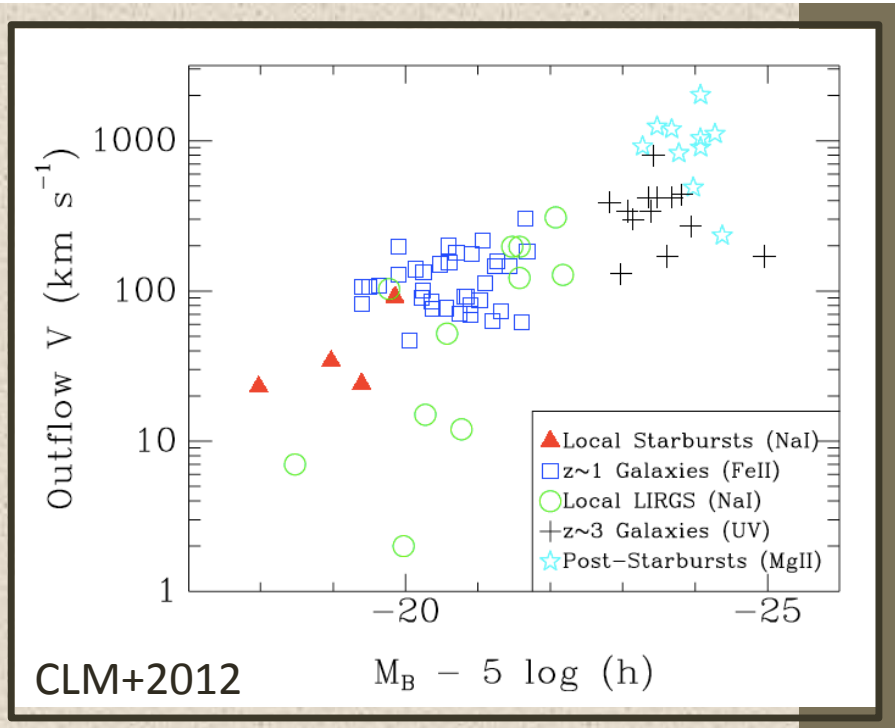
Feedback in Low Mass Galaxies

Observations of Outflowing Gas

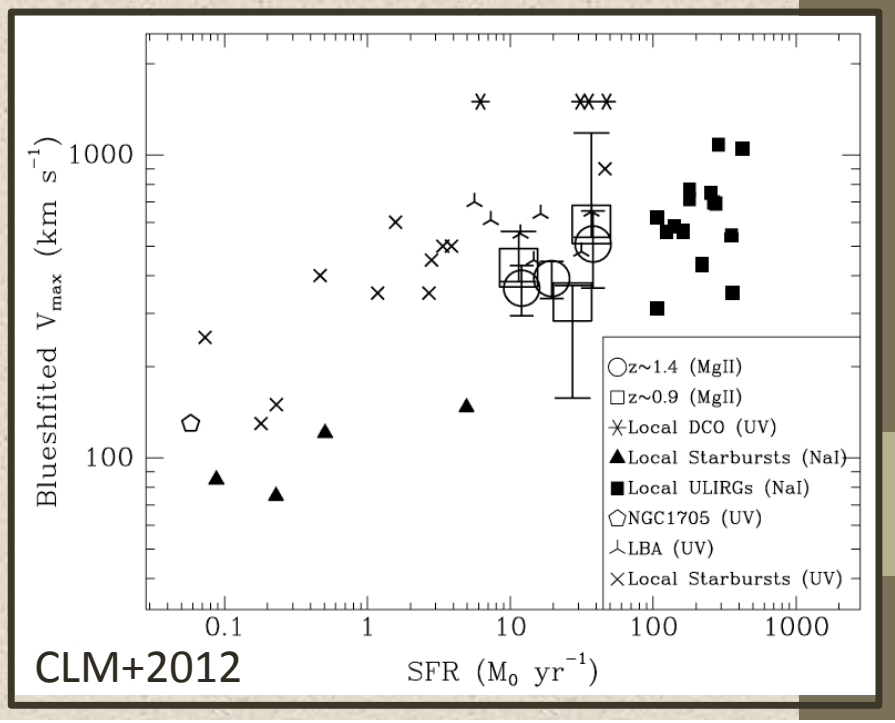
1. Galaxy spectra
   - Detect cool, outflowing gas within a few kpc of galaxies.
   - Defines scaling relations with galaxy properties.

2. Raise questions such as
   - Total mass flux?
   - Spatial extent?
   - Ejected or recycled?

3. CGM sightlines help.

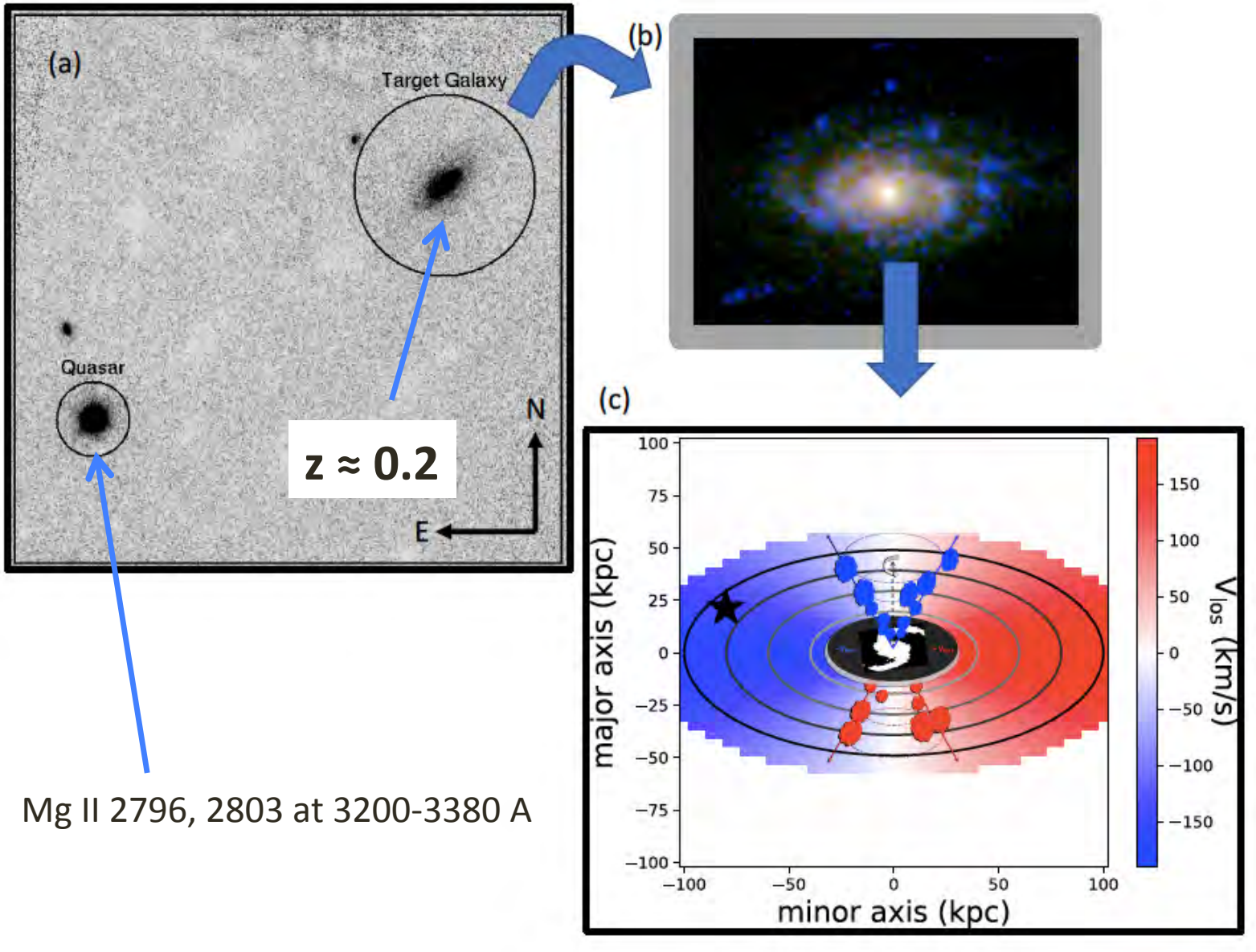


CLM+2012



CLM+2012

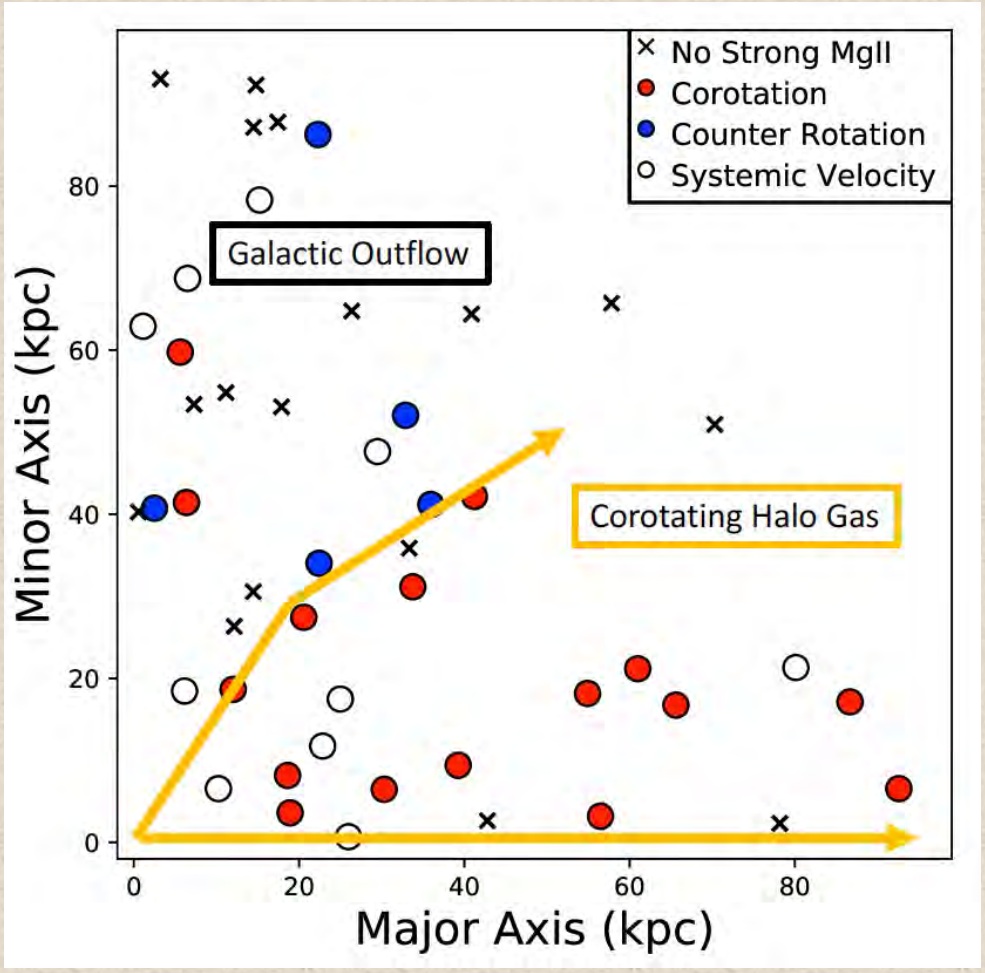
Quasars Probing Galactic Inflow



Mg II 2796, 2803 at 3200-3380 A

CLM, Ho, et al 2019, ApJ 878, 84

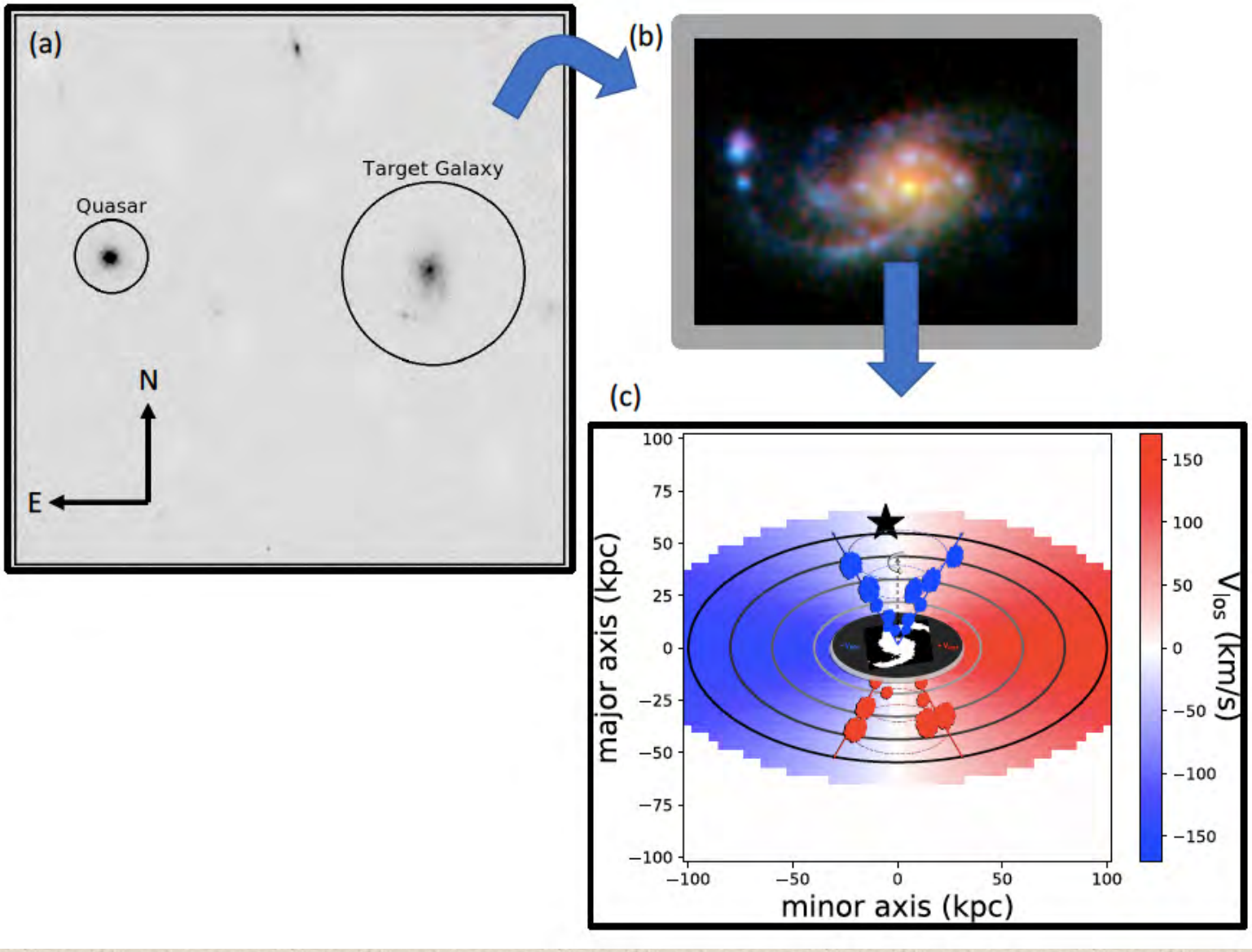
Minor Axis Sightlines: No Net Corotation



- *Left:* Stacking 50 quasar sightlines through the halos of 50 galaxies of log M*/ M_0 = 10.0.
- ELTs: Multiple sightlines per galaxy!

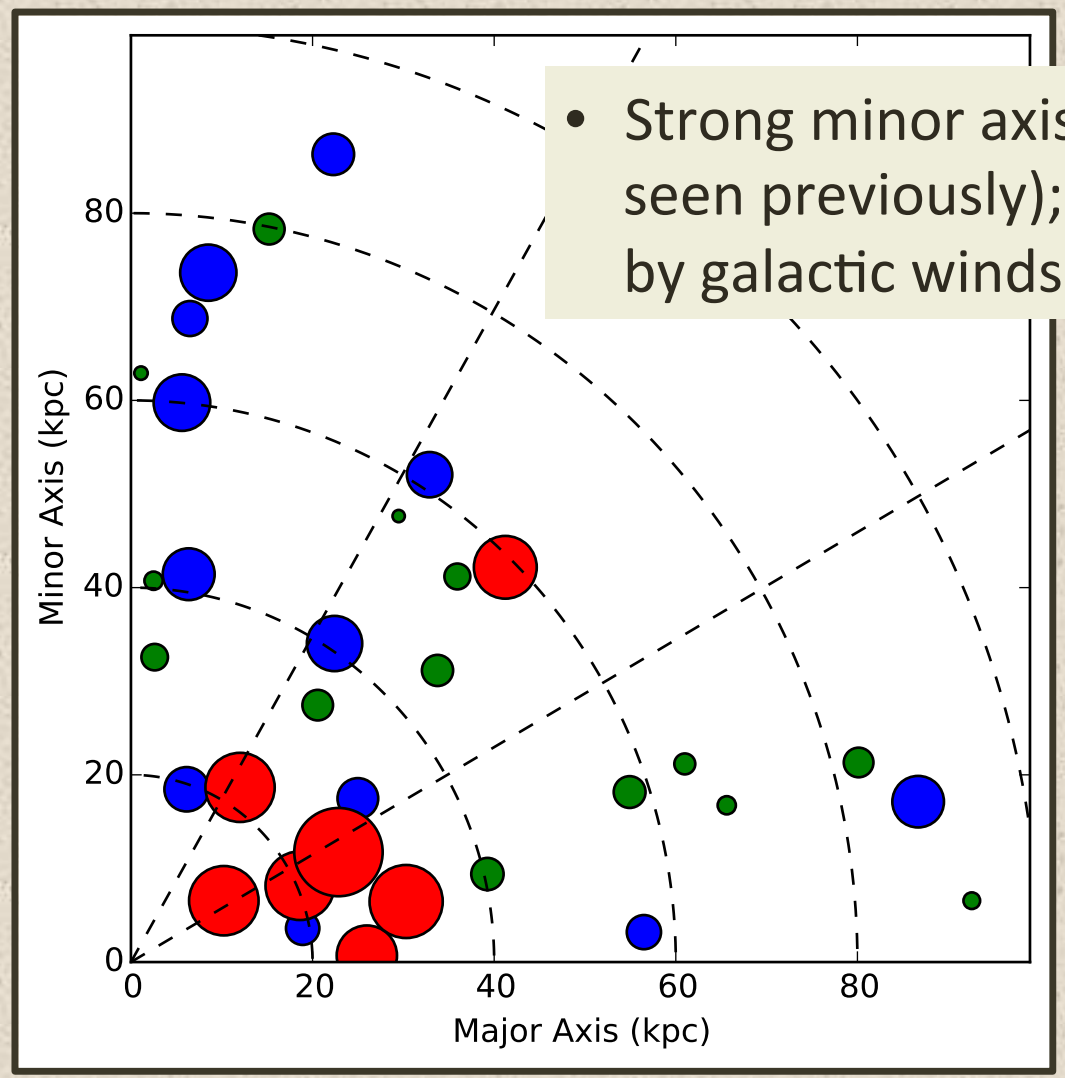
CLM, Ho, et al 2019, ApJ 878, 84

Quasars Probing Galactic Outflow?



CLM, Ho, et al 2019, ApJ 878, 84

Mg II Absorption Strength Depends on Azimuthal Angle



- Strong minor axis Mg II absorption (as seen previously); does it imply disturbed by galactic winds?

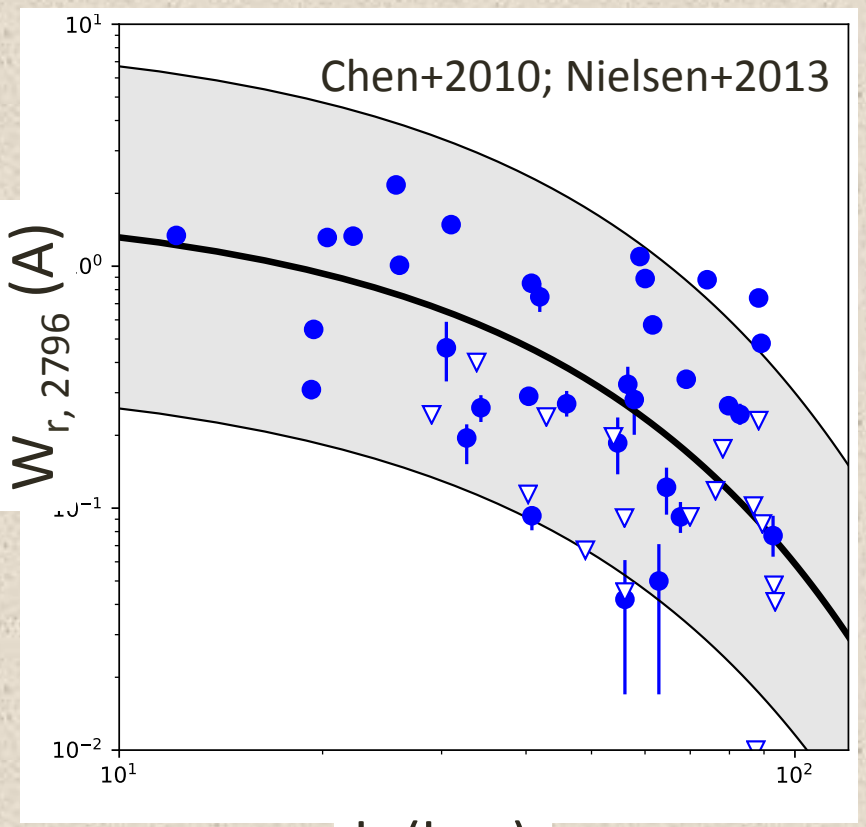
- Strong major axis Mg II absorbers (new); previous studies lacked sightlines at b < 40 kpc. These ALS are related to disks but are not thin disks.

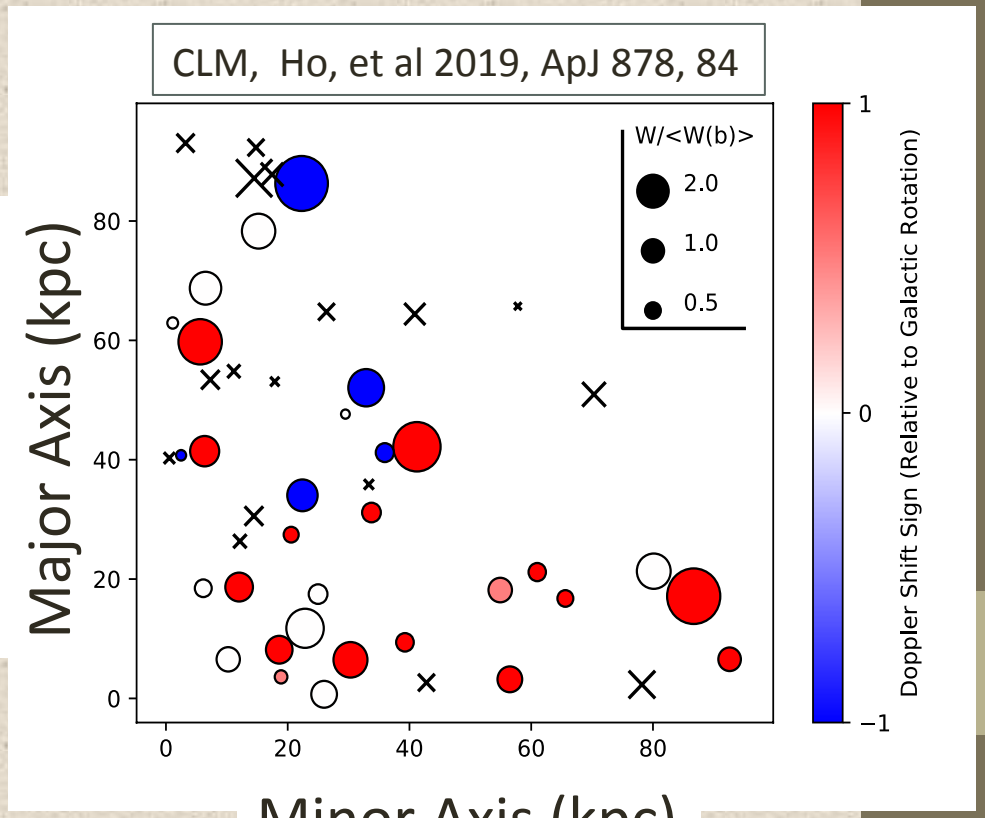
Symbol size (and color) indicate absorption strength.

CLM, Ho, et al 2019, ApJ 878, 84

Minor Axis Excess Absorption

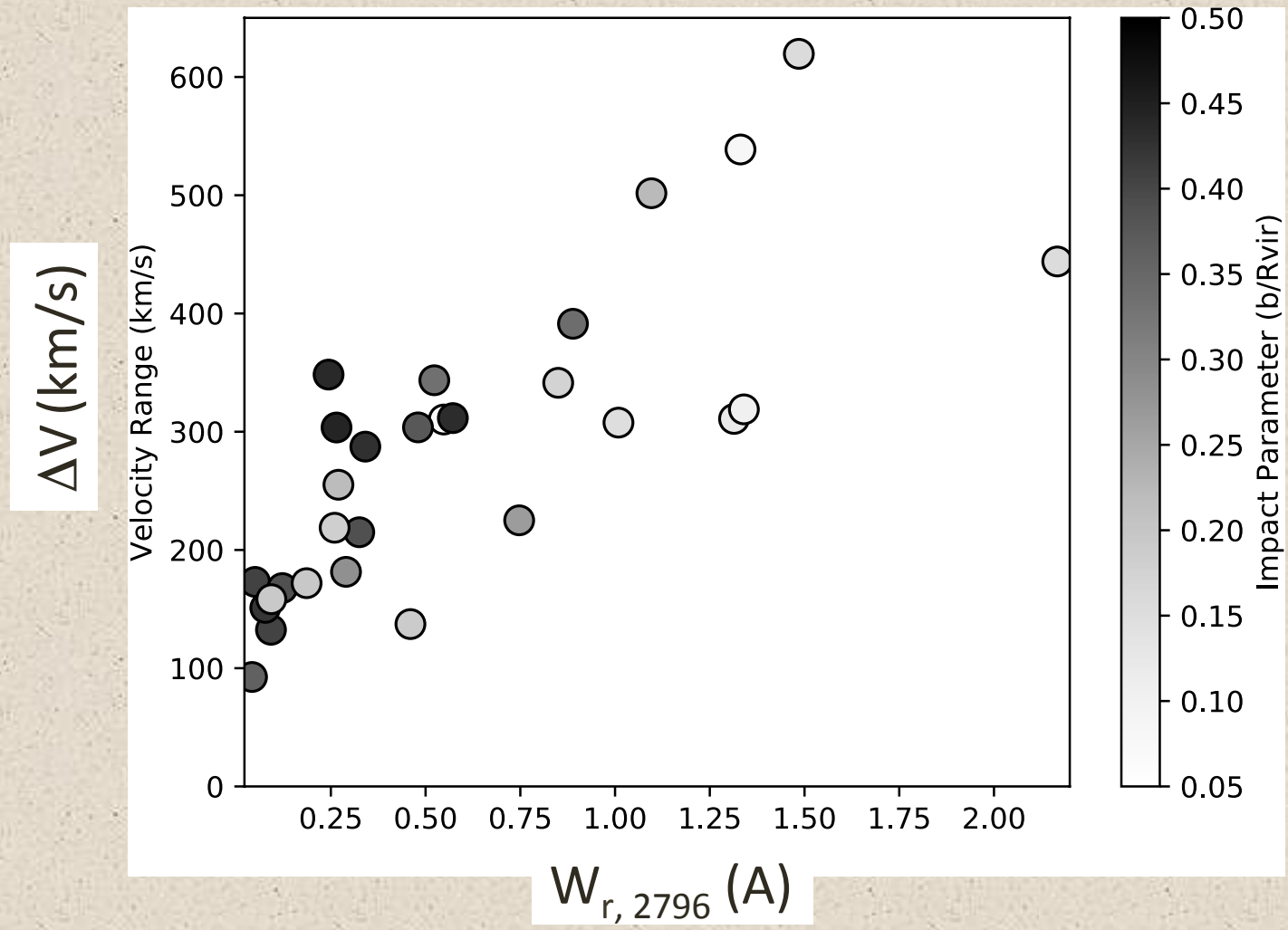
- Average equivalent width declines with impact paramete.
- Most ‘excess absorption’ is detected in minor axis sightlines
- We can show that this is a kinematic disturbance.





Confirm that Strong Absorbers Have Large Velocity Spread

We want to understand how outflows increase the absorption.



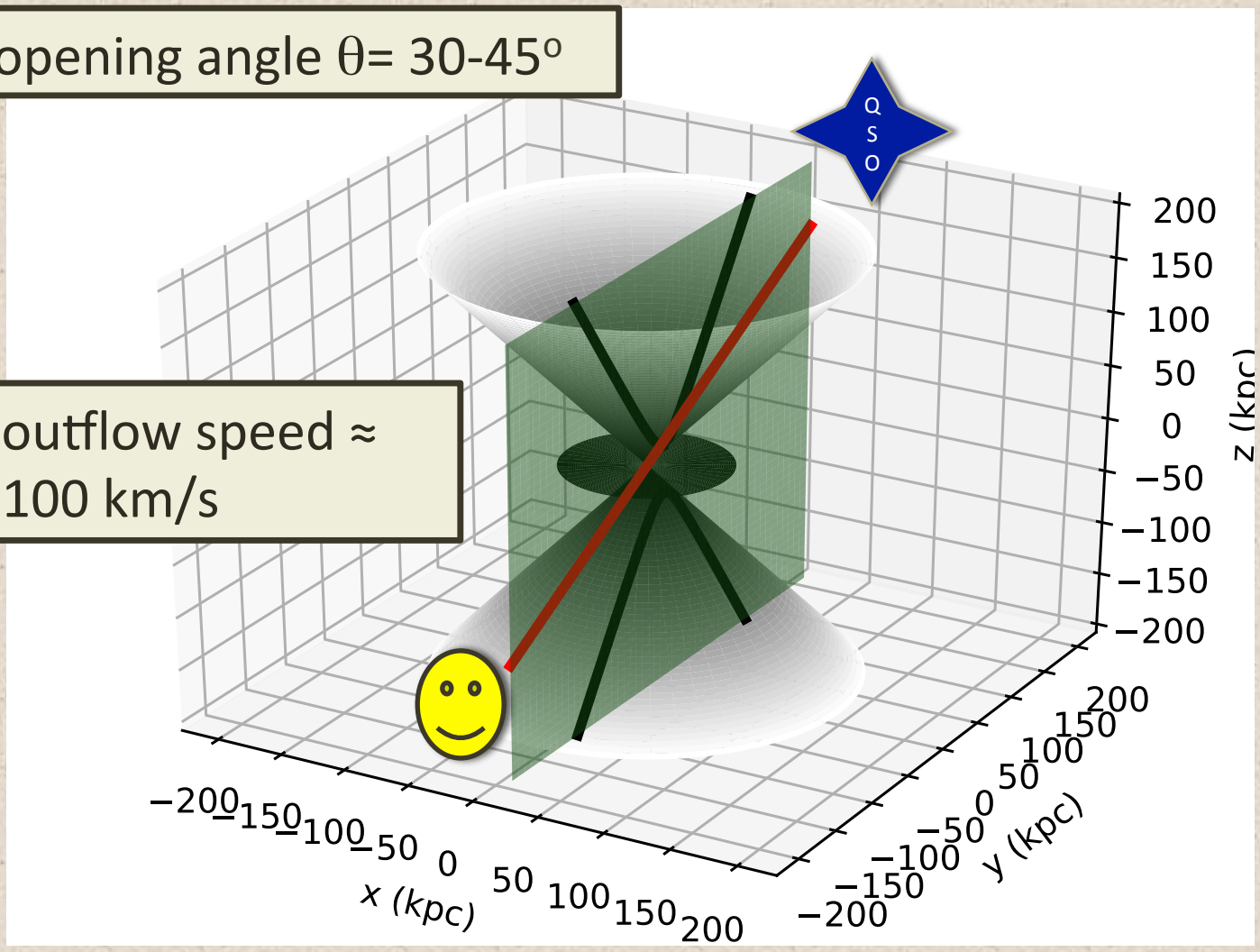
CLM, Ho, et al 2019, ApJ 878, 84

Conical Outflow Model

Motivated by Outflow Properties Measured from Galaxy Spectra

Cone opening angle θ= 30-45^o

Radial outflow speed ≈ few X 100 km/s



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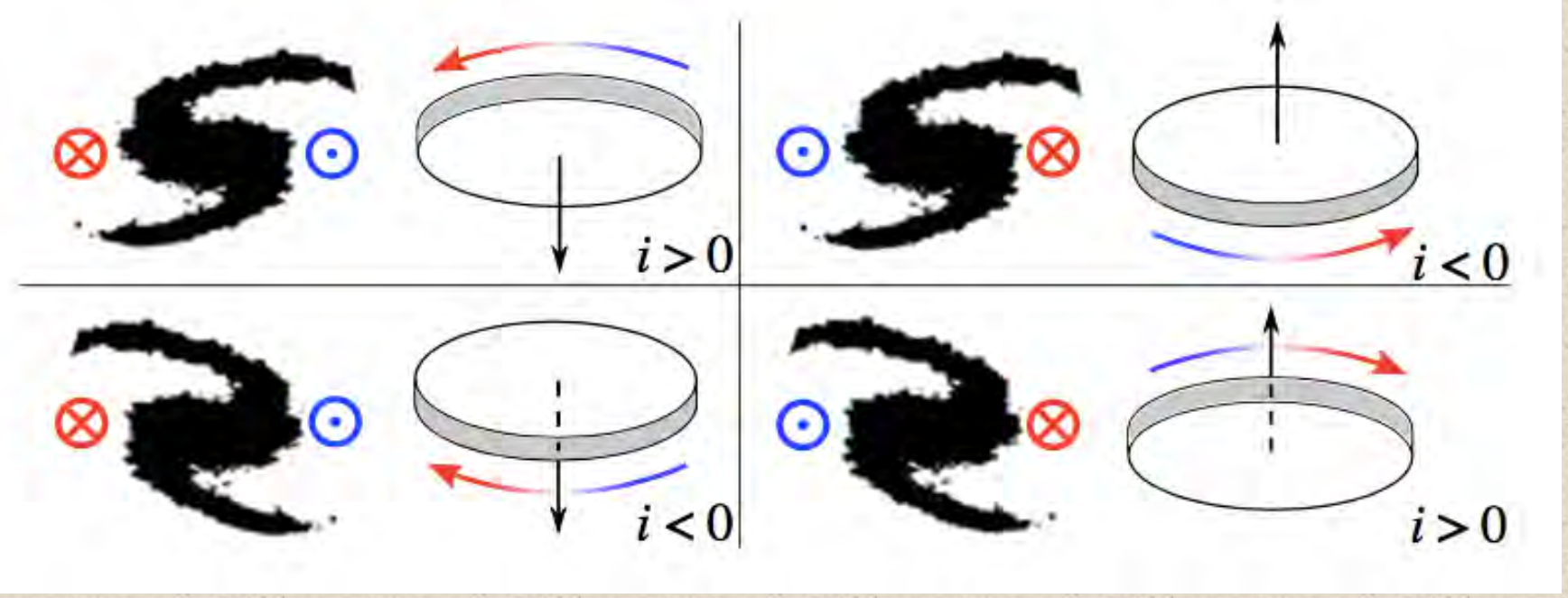
Determine 3D Orientation of Galactic Disks

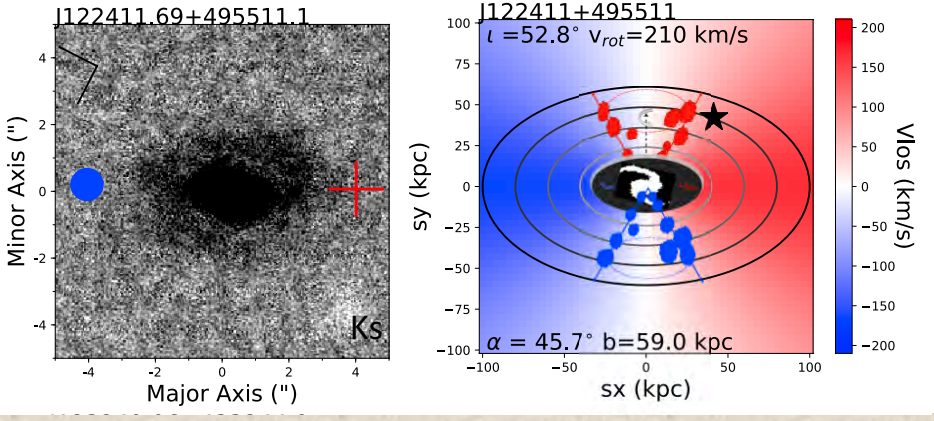
- Rotation curves are not enough.
- Which side of the disk is tipped towards the observer?

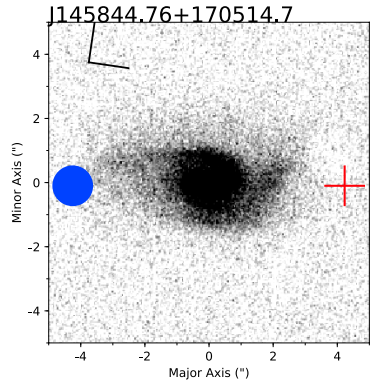


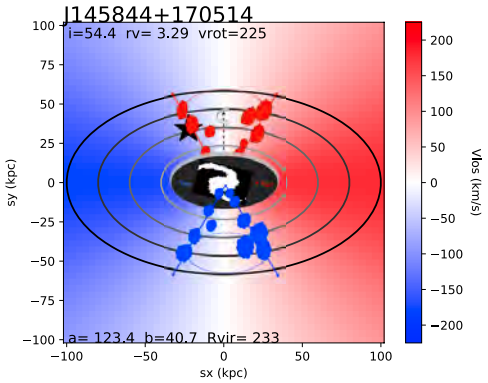
- Spiral arms are generally trailing.
- Resolving spiral arms determines 'disk flip,' or sign of disk inclination.

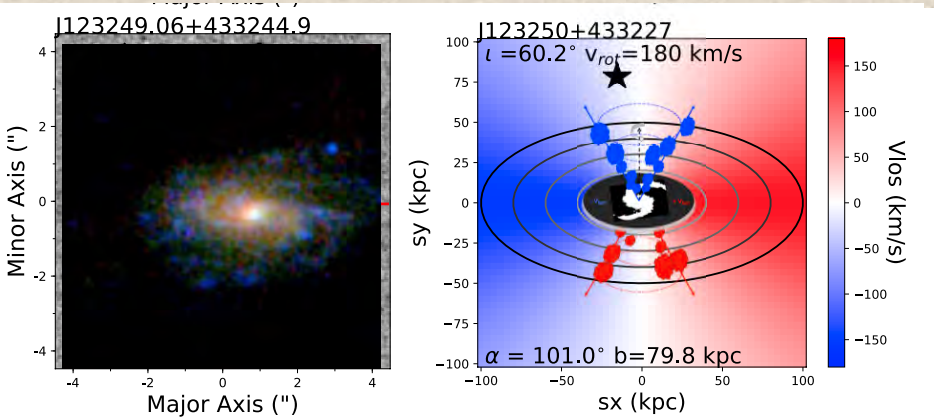
Ho &CLM 2018b

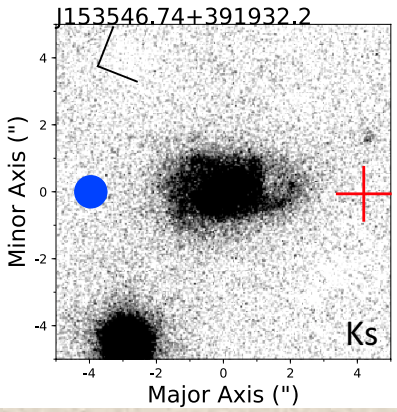
Measured 3D Orientation of Galactic Disks

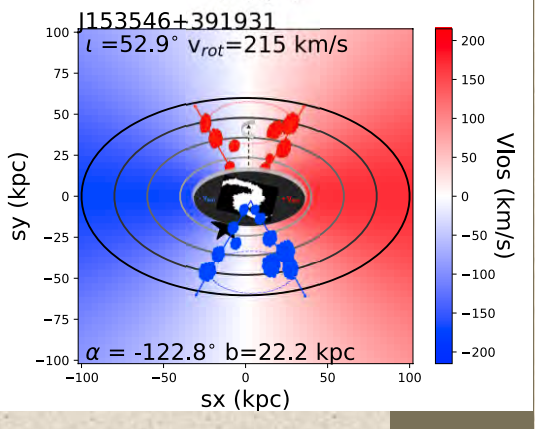


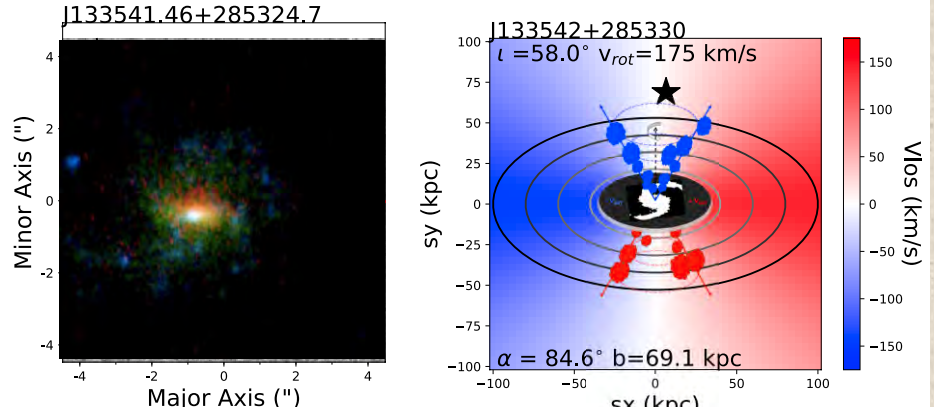


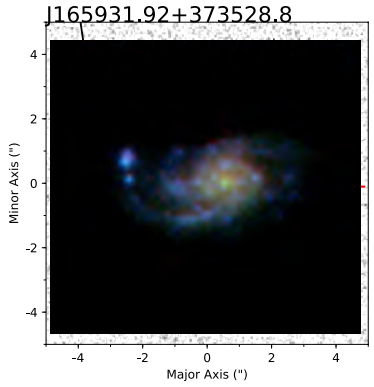


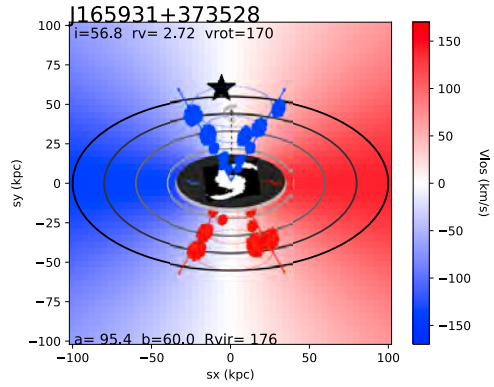






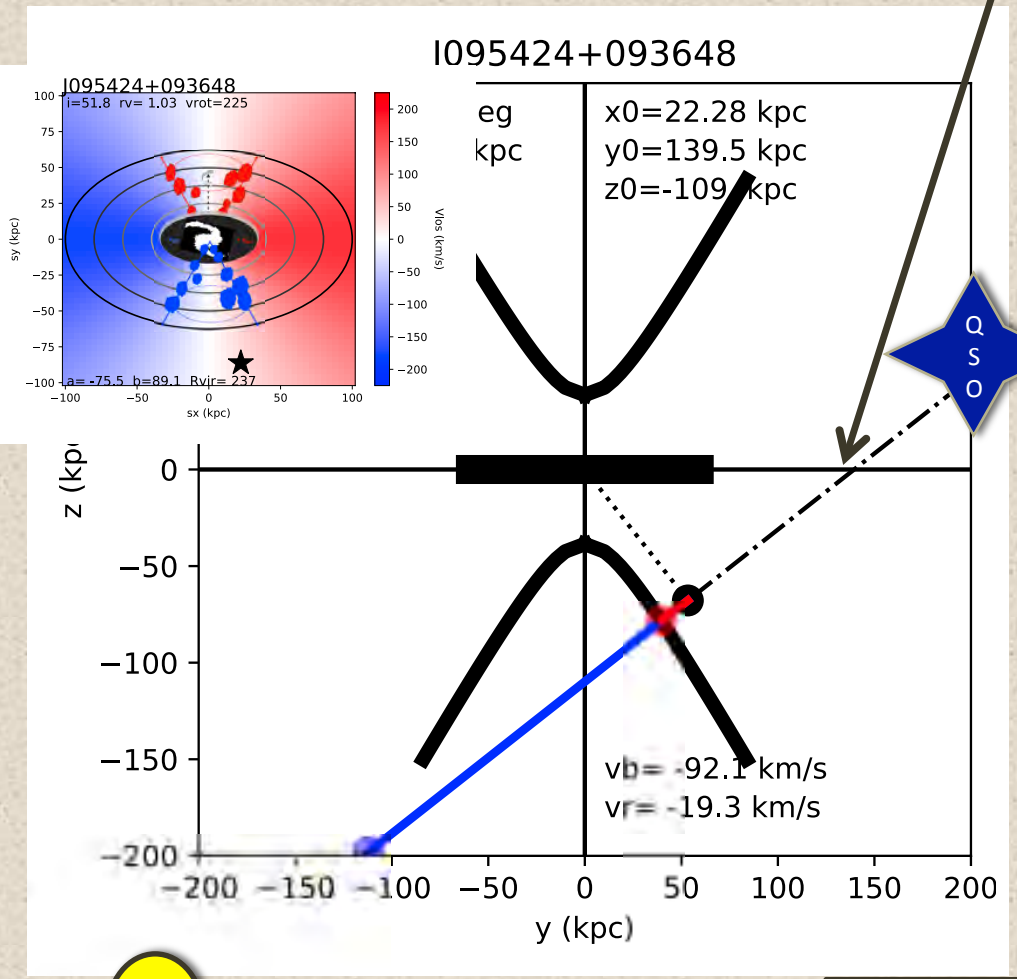




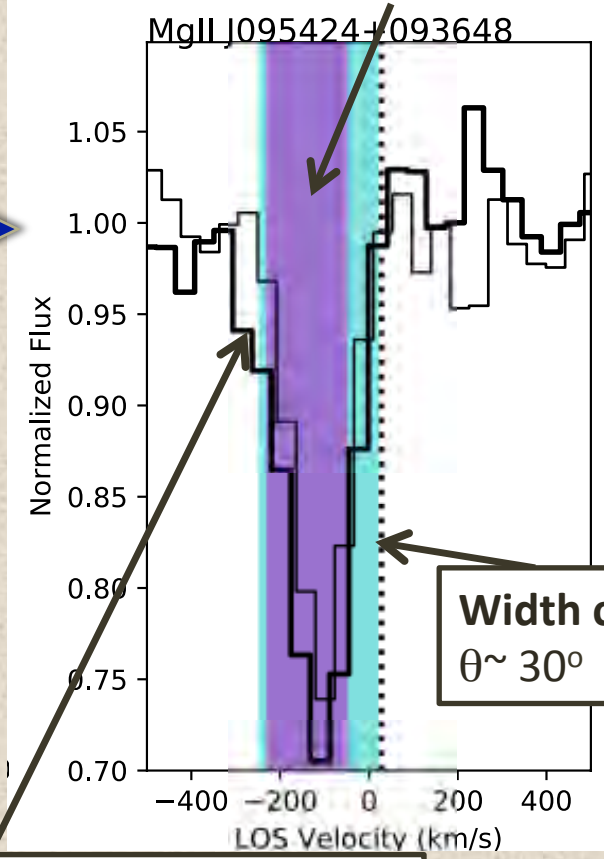


Minor-Axis Sightlines with Strong Mg II: Example with No Disk Component

R = 141 kpc, so sightline misses disk.



Doppler shift requires v = 180 km/s



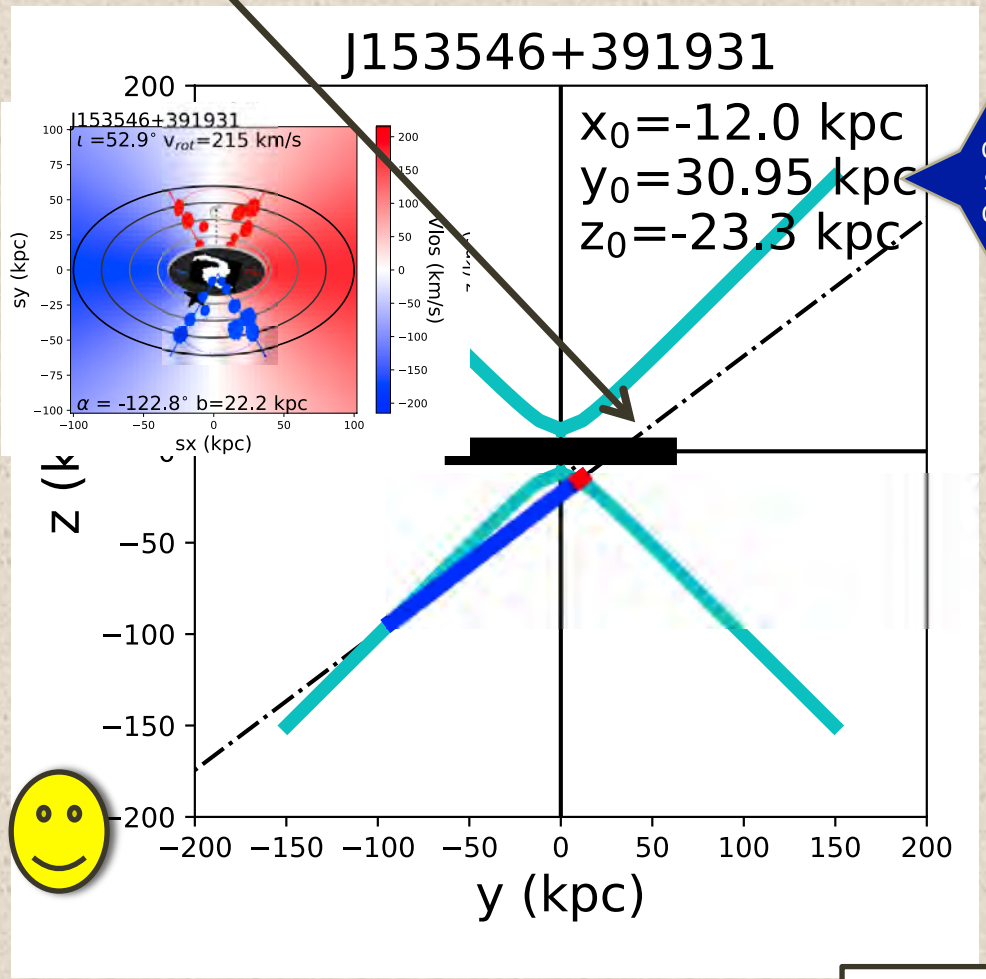
Width constrains $\theta \sim 30^{o}$

Is line wing part of outflow?

CLM, Ho, et al 2019, ApJ 878, 84

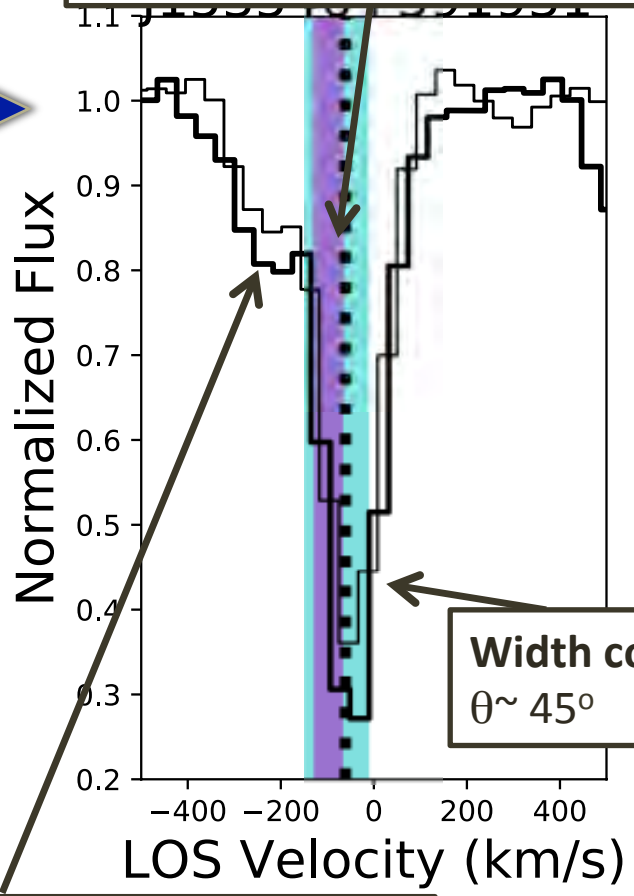
Minor-Axis Sightlines with Strong Mg II: Example with Possible Disk Component

R = 33 kpc, so not surprising that sightline intersects disk.



QSO

Blended disk and 150 km/s outflow components?



Width constrains
θ~ 45°

Is line wing part of outflow?

CLM, Ho, et al 2019, ApJ 878, 84

Correlation with SF Activity?

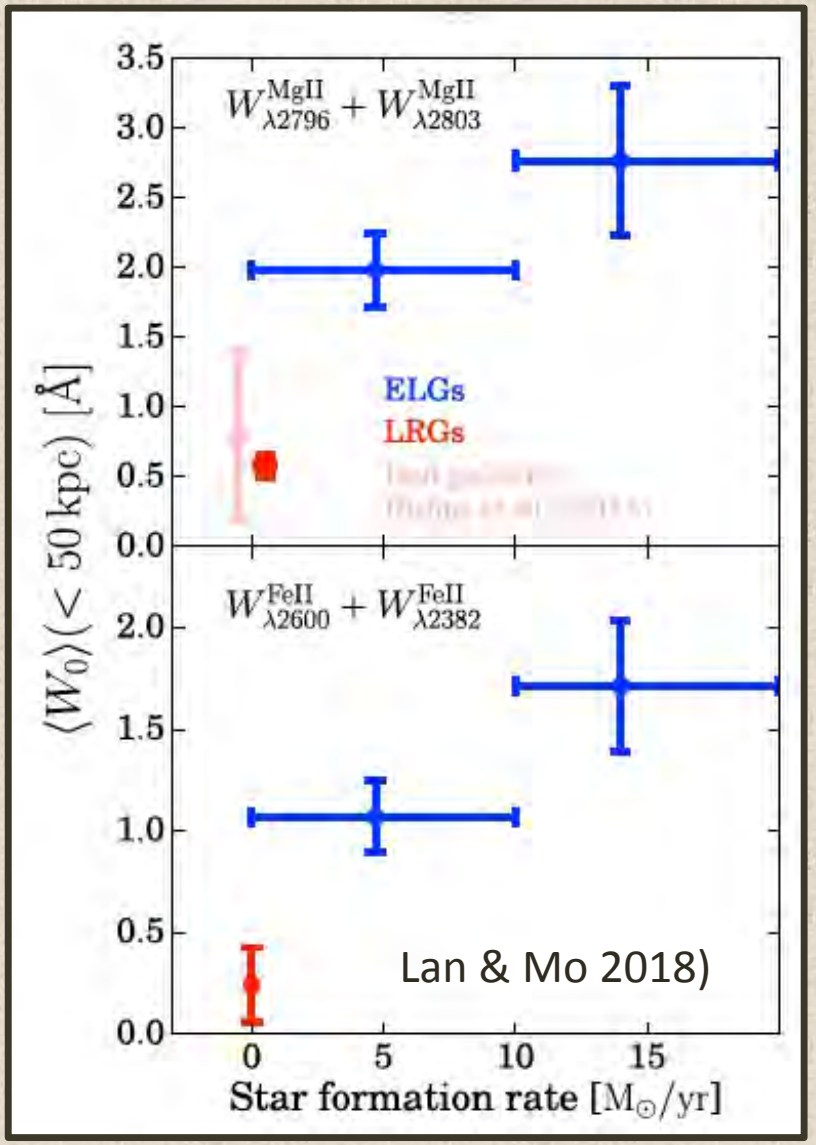
Timescales: $t_{flow} \sim r_{los} / v_{wind}$

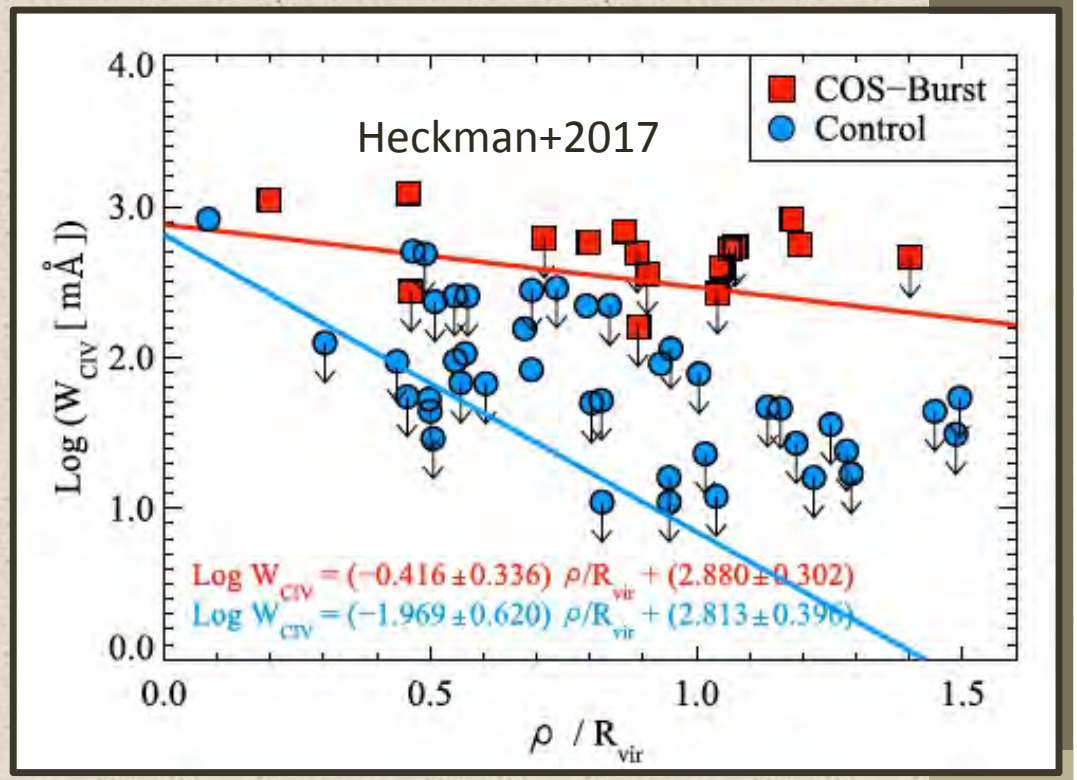
- **J095424+093648** (r_min = 89 kpc)
  - @1000 km/s, t_flow = 87 Myr
  - @ 100 km/s, t_flow = 870 Myr
- **J153546+391931** (r_min = 22 kpc)
  - @1000 km/s, t_flow = 22 Myr
  - @ 100 km/s, t_flow = 220 Myr

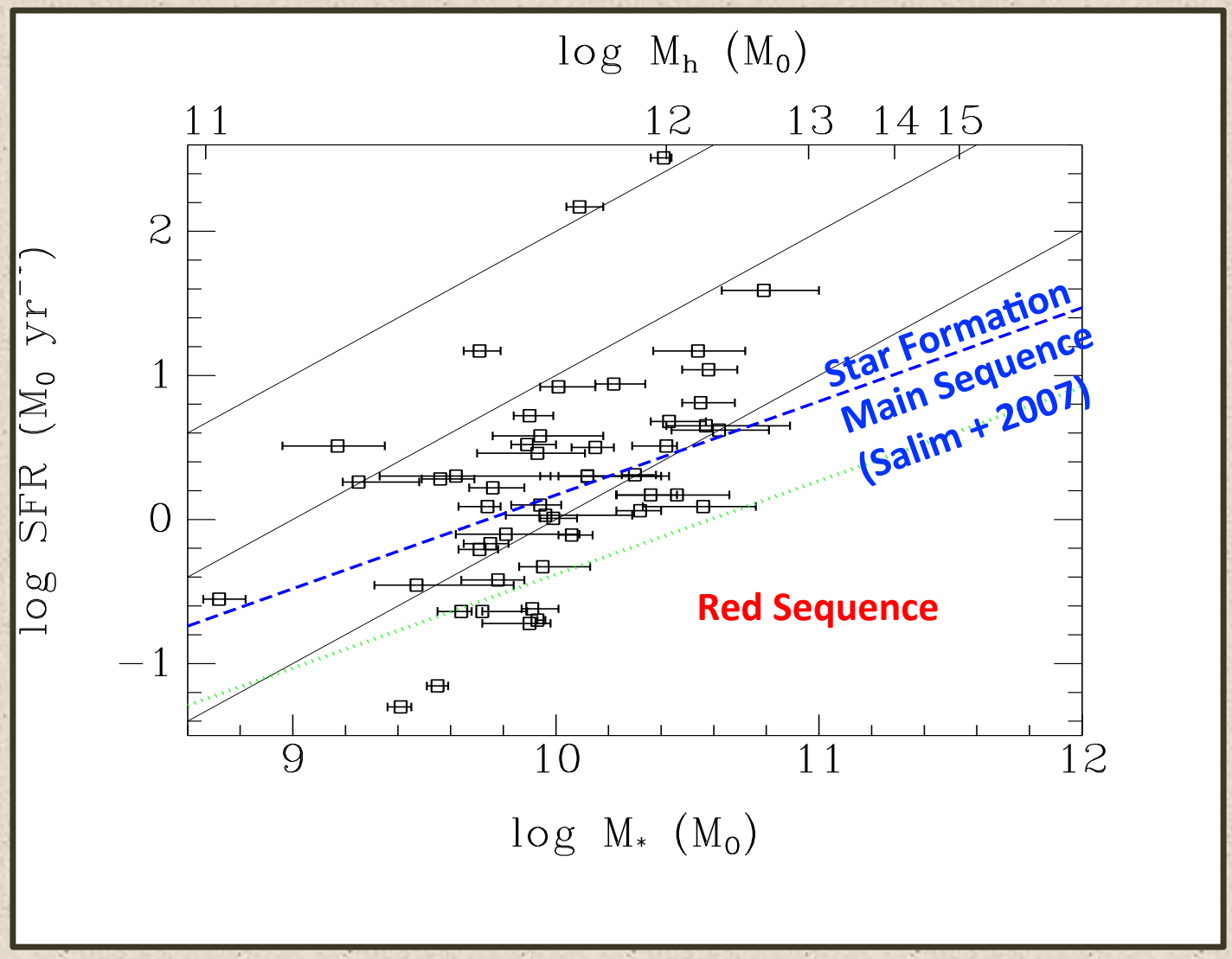
Do the host galaxies have elevated SFRS?

CLM, Ho, et al 2019, ApJ 878, 84

Population Statistics



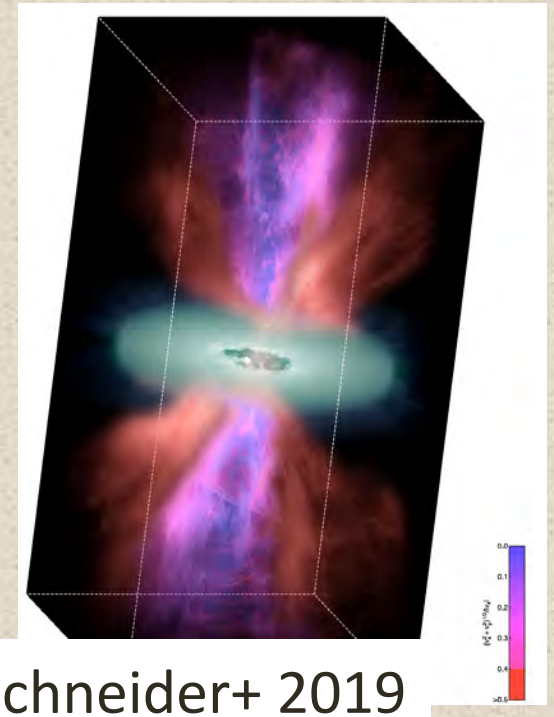




Yes, but they are within 1.5 sigma of the SFR main sequence.

Need to Link Models and Observables

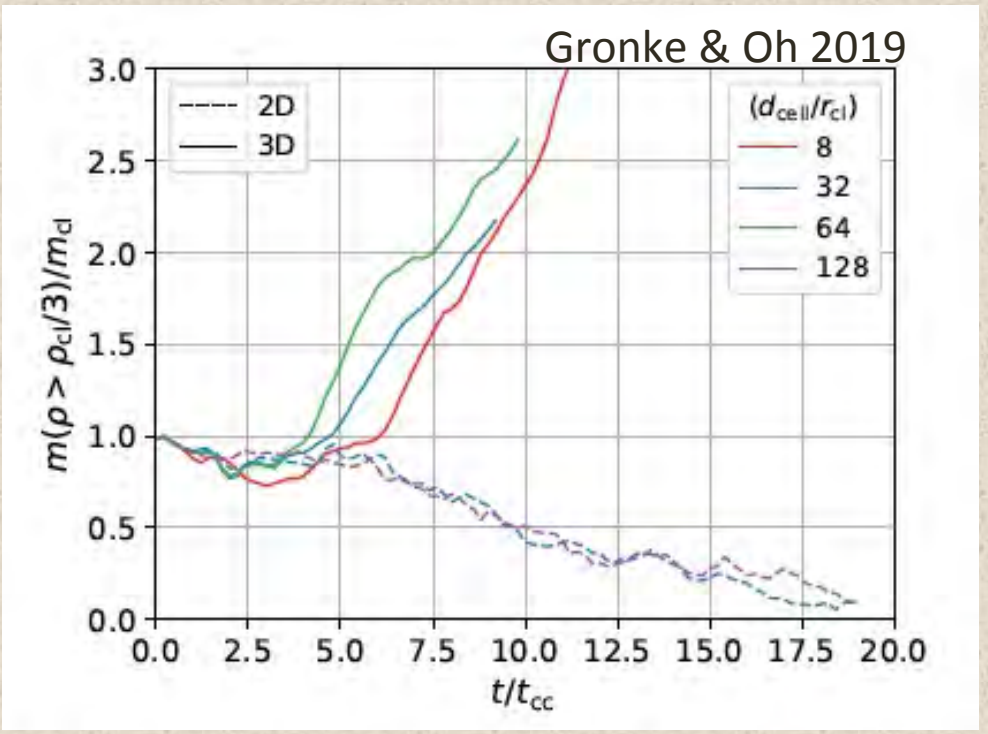
- Mass loading in starburst region vs. significant mass entrainment from CGM
  - High-resolution spectra ➔ component velocities and column densities
  - Estimates for mass flux depend on assumptions about the flow.



Schneider+ 2019

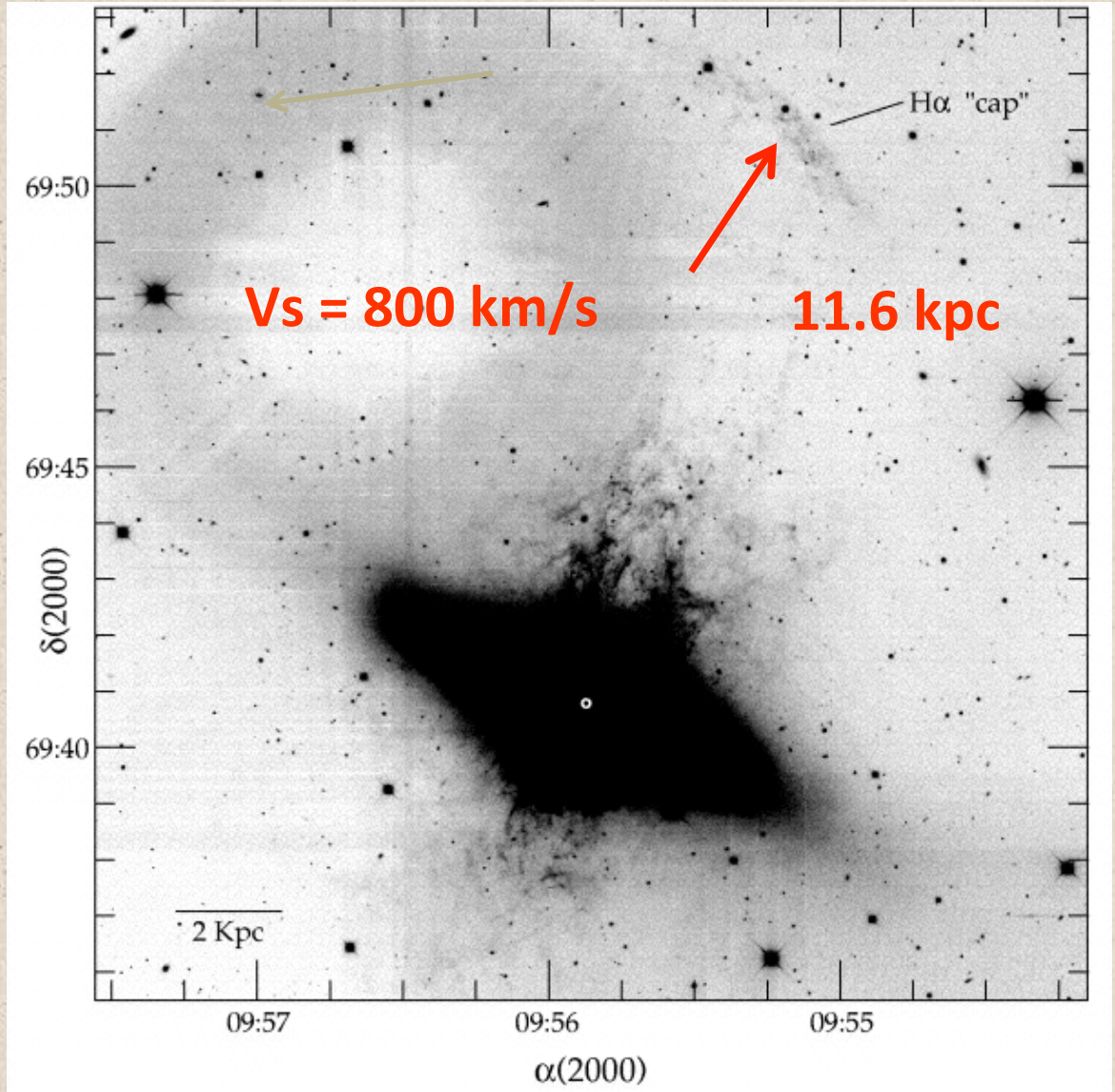
Mass loading

Gronke & Oh 2019



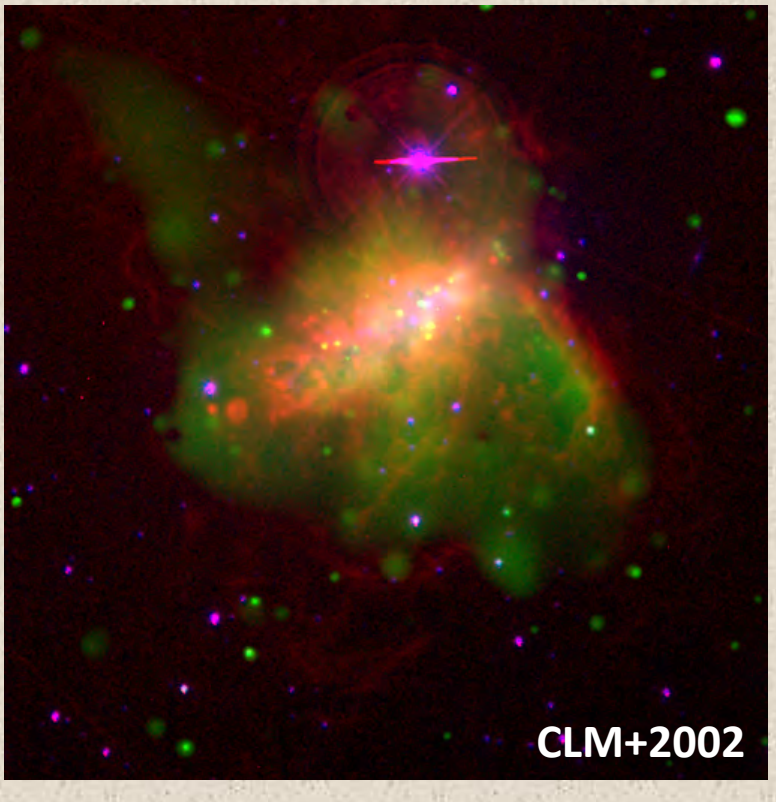
Cloud moving outward

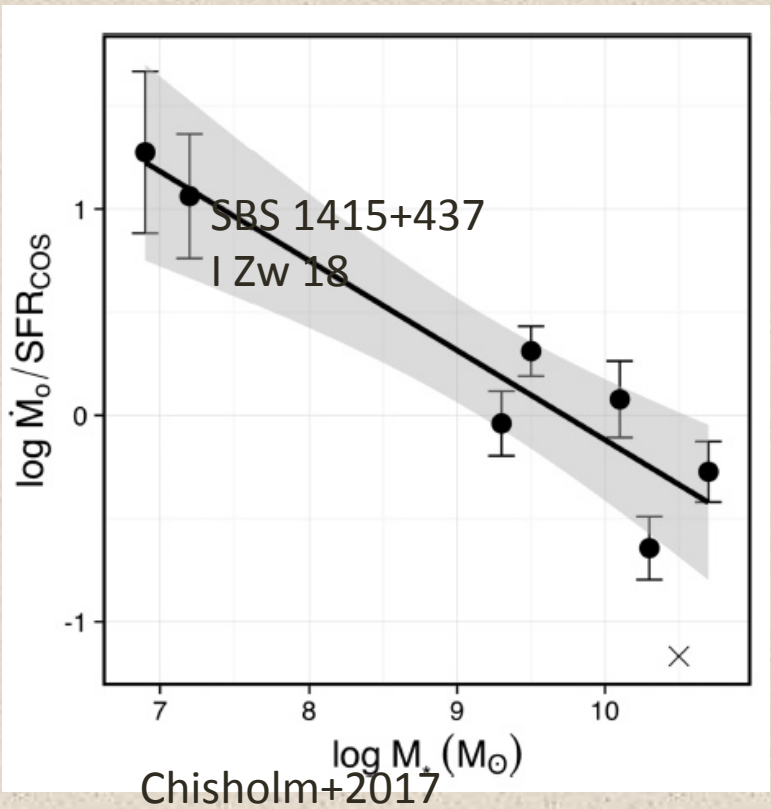
Outflow – CGM Interaction



Devine+1999 ; Lehnert + 1999

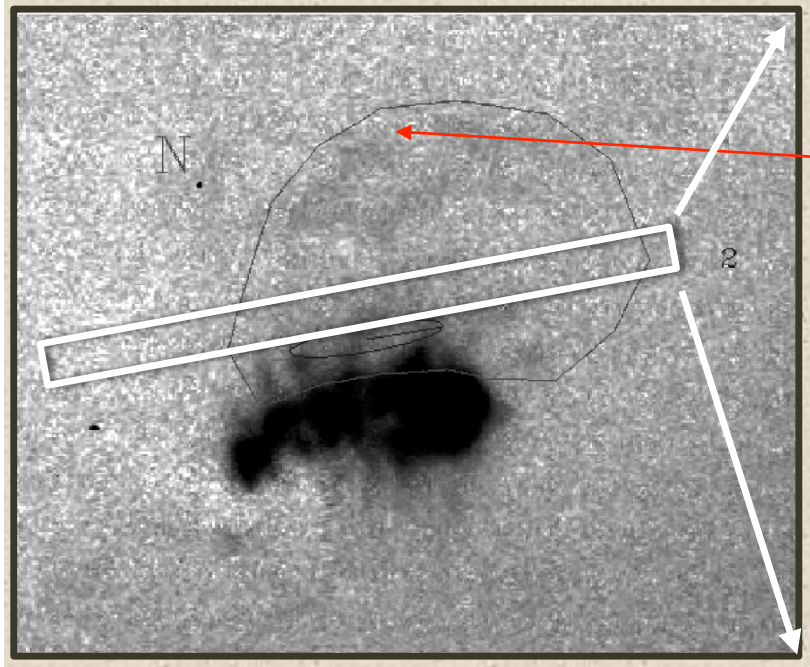
Feedback in Low-Mass Galaxies

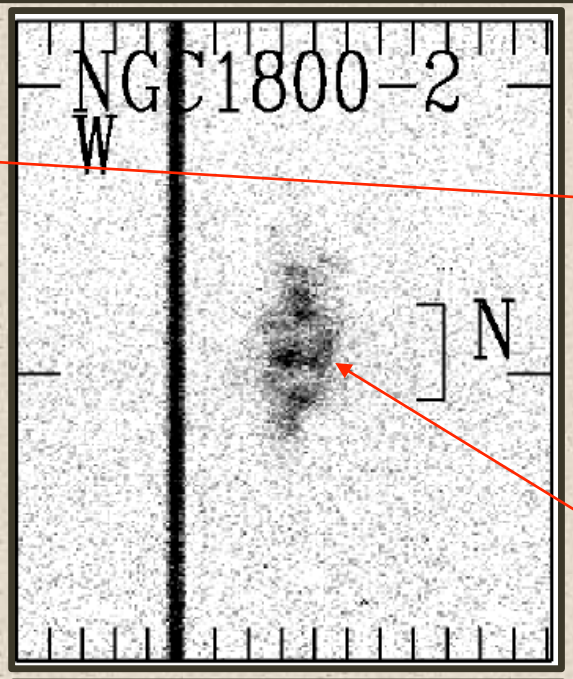




Chisholm+2017

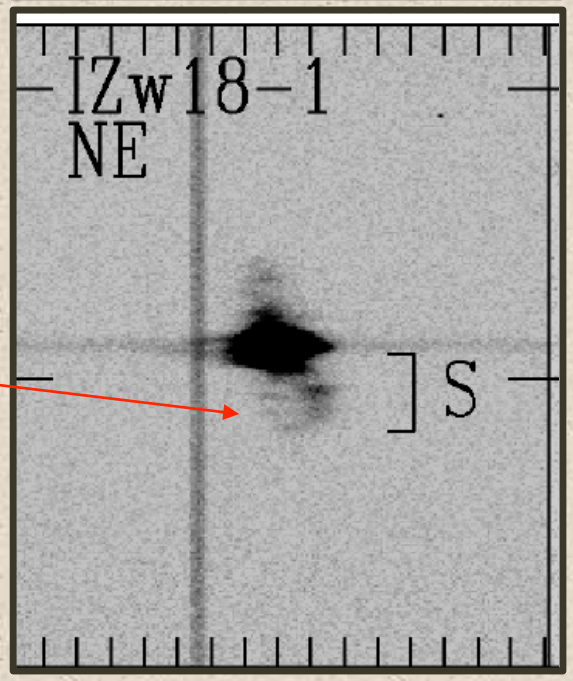
Example: 10 Mpc Sample (CLM 1998, 99)





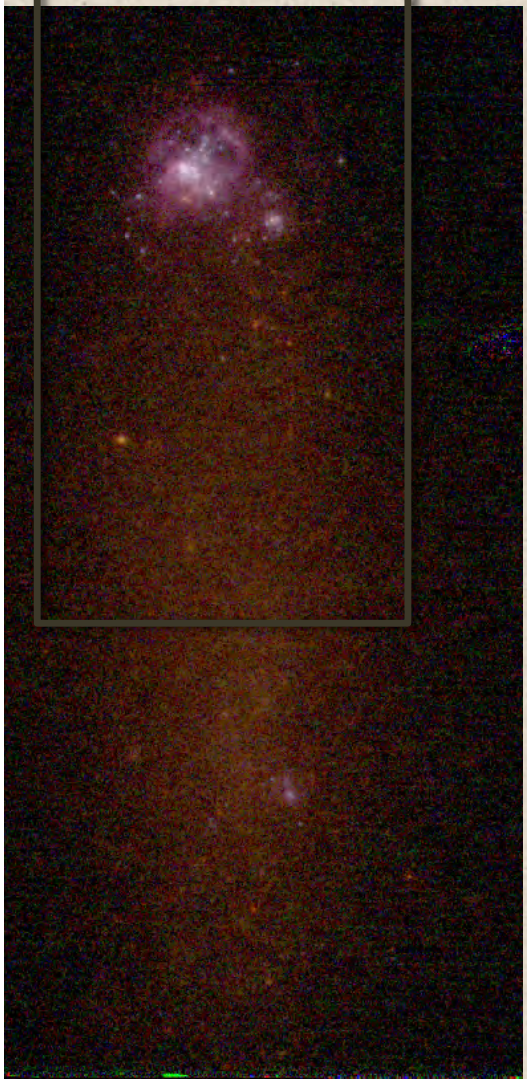
Ionized-gas detected 1.4 kpc above star-forming regions.

Echelle spectrum resolves near and far sides of expanding shell. *Tick marks are separated by 46 km/s.*

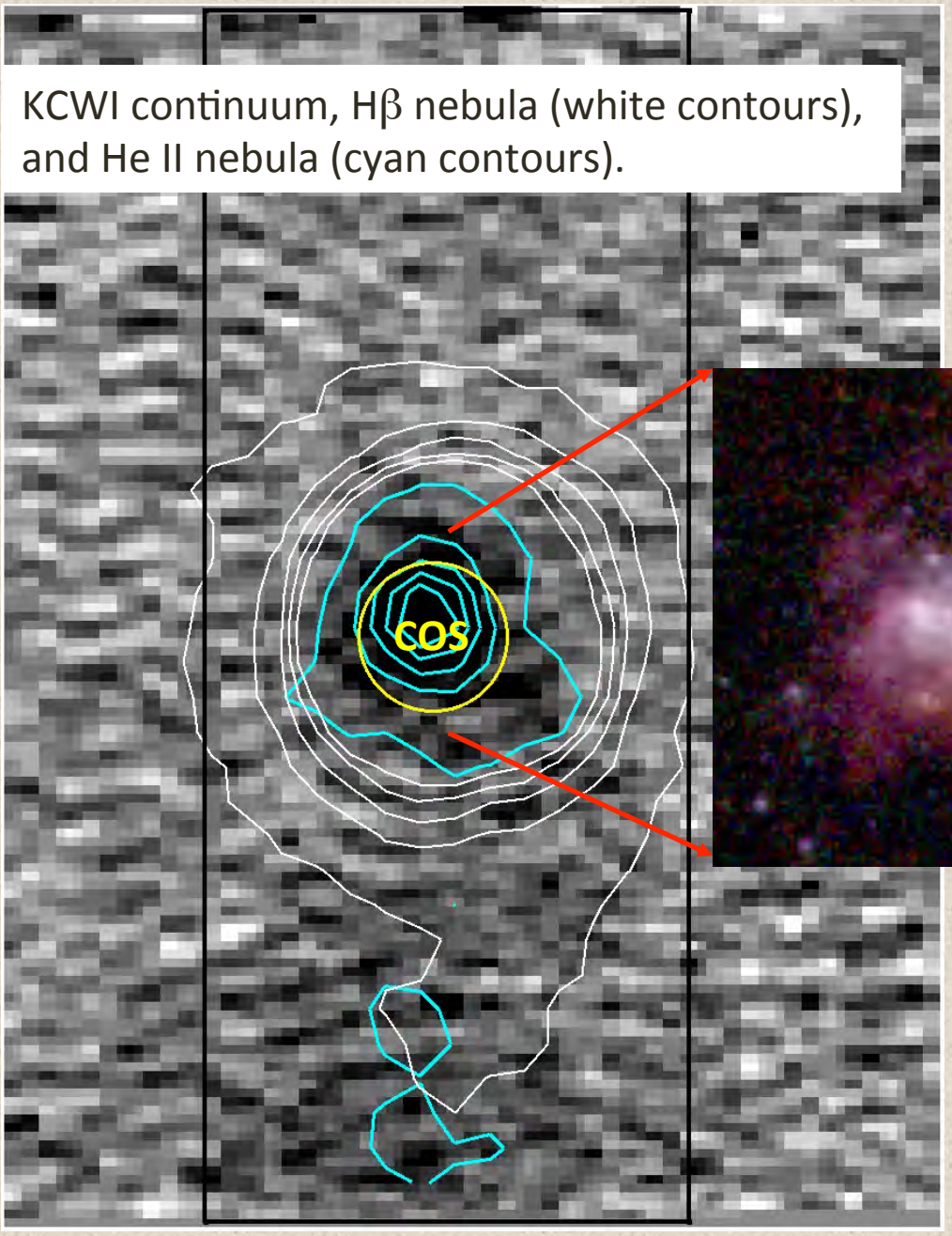


Shell extending 1 kpc
V ~ 34 km/s

KCWI
Slicer on HST
image



KCWI continuum, Hβ nebula (white contours), and He II nebula (cyan contours).



Summary & Outlook

- Impact of winds on CGM directly observed! Excess Mg II absorption in minor-axis sightlines is well established.
- The value of spatially resolved galactic rotation and morphology has previously been underestimated.
    - Need to explore the nature of the line broadening observationally and theoretically.
    - Demonstrated stacking 50 sightlines, but ELTs will provide access to multiple sightlines per galaxy.
- Challenging to find evidence for very high mass loading (> 20) in low mass galaxies. Stay tuned!
    - KCWI study of highest sSFR dwarfs at d < 60 Mpc
    - COS Legacy Archive Spectroscopic Study (Berg, PI +)